distance, frequency, and antenna heights; it is a normalized distance that attempts to put all paths into a common mold. In practice, one speaks of the median V(0.5) and of the quantiles of the deviations--which are now denoted by y(t)--from this median. In Figure 5, we show the curves of these quantiles versus effective distance for the case of the "maritime temperate over land" climate. Except for the design of the effective distance, such curves are entirely empirical; they have been drawn through measured values that exhibit, unhappily, a rather large spread.

Nevertheless, the method performs fairly well. This is attested to in the report by Longley et al. (1971), which summarizes data from a large number of paths and compares the observed cumulative distributions of hourly medians with those provided by this method.

The method was originally prepared to treat the case of those paths over which the dominant mode of propagation is tropospheric scatter. It was then extended to include shorter paths. Ducting phenomena, however, have never been satisfactorily included. In Figure 5, there are some large upswings at large effective distances for the very low percentiles. This represents an attempt to describe the enhanced fields that arise, presumably, from the presence of ducts. But this refers to the "normal" antenna towers in the presence of the "normal" duct heights that appear in a maritime temperate climate--which probably means the North Sea since that is the region used to epitomize this climatological type. There is no attempt made to allow for other situations. In general, we would suppose that pegging the enhanced fields caused by ducting to the "reference" level can never be satisfactory.

The method just described tries to portray the entire range of time variability. A second method--one that concerns only the enhanced fields present for very small fractions of time--was first suggested by Misme (1974) and is now a method given by the CCIR (1978b). It speaks of a "leakage coefficient" into and out of a presumed duct and of a "minimum coupling distance" into the duct. It gives a formula for the attenuation relative to free space directly without the mention of a reference level. The formula is most obviously a function of the path length but the coefficients involved depend on the average initial lapse rate of refractivity, the frequency, the terrain irregularity parameter Δh, and the proportion of the path that lies over sea. The method is designed for quantiles of 1% or less and for frequencies between 600 MHz and 15 GHz.

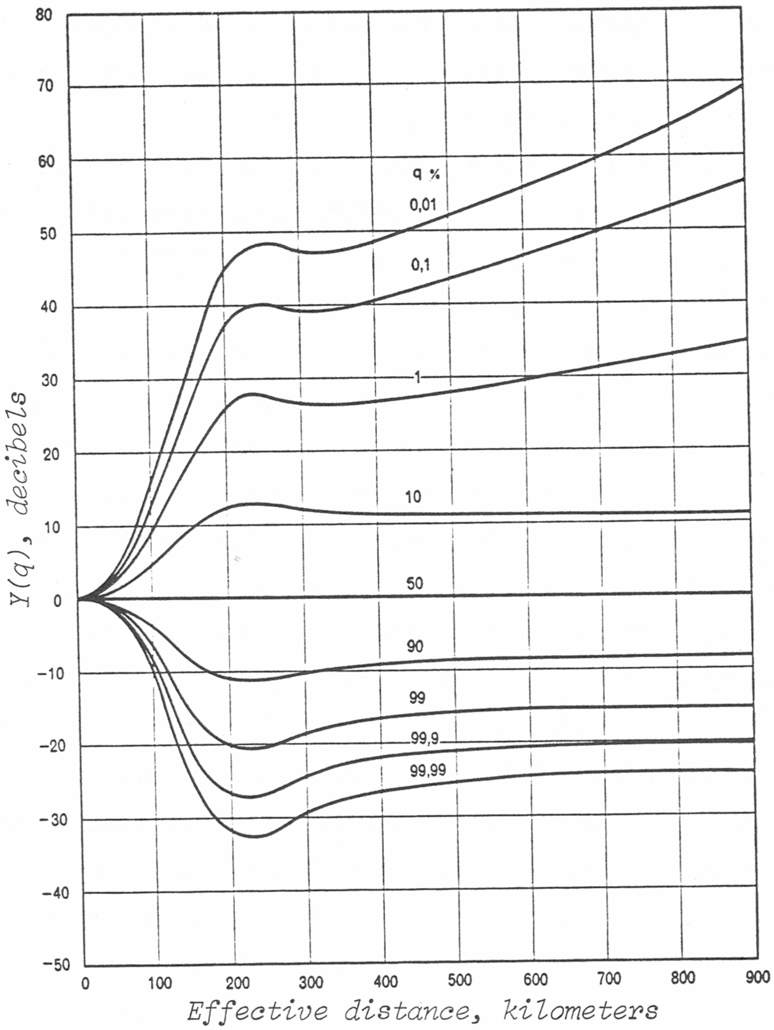

Figure 5. Quantiles of deviations versus effective distance for the maritime temperate climate over land. Adapted from CCIR (1978a).

This approach has many of the features that seem desirable to us; the limitations seem severe but could probably be relaxed with further study. On the other hand it seems a little artificial to use the average initial lapse rate of refractivity to categorize the incidence of ducts and their characteristics--other climatic parameters would probably be more suitable. Another parameter that is missing from the method is the antenna elevation and how it relates to the possible duct elevation; this seems important to us.

In general, we would expect signal levels in the presence of a duct to depend on the depth, strength, and extent of the duct and on the radio frequency and the path geometry. Thus, the statistics of signal enhancement will depend on these factors and on the frequency of occurrence of ducting layers. Path geometry is important because it is at grazing incidence upon a ducting layer when effects are most pronounced. As the ray elevation angle is increased from 0° to perhaps 5° (about 85 mrad) the effects become negligible. Enhancements can be as great as 40 dB above the long-term median for transhorizon paths. On line-of-sight paths (perhaps 50 km long) signal levels 6 dB above free space are not unknown.

If a radio transmitting antenna is <u>above</u> a horizontal ducting layer, the usual effects are multipath fading and extended range while radio holes and antiholes may also occur. If the transmitter is <u>within</u> the layer, extended range occurs along and below the layer so that if both transmitter and receiver are within the layer, an enhanced signal level may exceed the free space level for great distances. This can happen because within the duct there is an inverse distance dependence, while in free space the decrease in signal level is proportional to the square of the distance. If an elevated layer is very much <u>above</u> the normal path of a radio ray, the duct will have little, if any, effect on propagation losses.

With these considerations in mind, we would suppose that a good, widely applicable model of signal level statitics on a given path would:

(1) postulate a small number of atmospheric conditions including "normal" atmosphere and atmospheres containing ducts of various characteristics

(2) calculate statistics of signal levels for each of these atmospheric conditions

(3) mix these "modes of propagation" according to the frequency of occurrence of each of them in the region involved.

To support such a model it might be sufficient to know simply the frequency of occurrence of surface-based ducts and the frequency of occurrence of elevated layers, this latter to be supplemented with a probability distribution of layer elevations.

3. THE MEASUREMENT PROGRAM

Accompanying our attempts to model signal variability in a ducting environment is a measurement program that uses specially constructed receiving systems to measure and record signal levels from "signals of opportunity." These systems were put into service in the San Diego area in September 1981. The transmitters to which they were tuned were mostly television transmitters in the Los Angeles area about 180 km to the northwest. The systems remained there until August or November 1983, thus giving us what appears to be about 2 years of data. Unfortunately, there were extensive down times and the resulting records are very spotty.

One of the systems was subsequently taken to Boulder, Colorado, and put into service in February 1984. It has since been recording data from a single television station in Pueblo, Colorado, about 190 km to the south.

We want here to describe the equipment used, the propagation paths for which signal levels were measured, and some first-order statistics that were obtained.

3.1 Automated Propagation Measurement System Equipment Description

The automated propagation measurement system is a special-purpose, microprocessor-controlled receiver. Its function is to receive and record the levels of up to 10 signals in the VHF and UHF ranges for long periods of time. The system tries to fill the need to be able to collect long-term radio propagation data while demanding only a small amount of routine maintenance. The system includes the important features of self-calibration under full control of the microprocessor and self-restart following a power failure.

Near the end of each hour the system will print a summary of the data collected during that hour. The summary gives a number of points on the received signal level distribution for each of the programmed frequencies. In addition to these statistical data some selected values from the calibration process for the current hour are printed. Finally, all of the signal level data collected during the hour, all of the calibration information, and some necessary bookkeeping data are written onto magnetic tape. The routine manual maintenance, therefore, involves changing the computer terminal paper and the magnetic tape.

The measurement system is composed of two major subsystems--the receiver and the microprocessor. The receiver subsystem, shown in block diagram format in Figure 6, includes components such as the antennas, the antenna control box, the local oscillator (a commercial frequency synthesizer), and the receiver chassis itself (a five-plug-in module device). The microprocessor subsystem is physically divided into several components including the digital tape deck, the computer terminal (keyboard and printer), and the microprocessor chassis. There is one more component of the microprocessor subsystem, and it is probably the most important component of the entire system--the software programs. These not only control all of the functions of the system, but also digitize and record the received signal level data.

Signal energy enters the receiver via one of three receiving antennas. These are connected to an antenna calibration box located nearby at the top of an antenna tower. Particular antennas used are chosen and aimed to acquire the signals from the particular desired signals. For the San Diego measurements the most often used was a horizontally polarized log-periodic antenna with a frequency range from 150 to 1000 MHz. Antennas for the remaining two positions varied with the particular receiver site. Two examples are a yagi tuned to 868 MHz, and another yagi tuned to TV channel 3 at 60 MHz. Proper antenna polarization depends, of course, on the source.

During propagation measurements, the antennas are connected through the antenna calibration box directly to the receiver input. During a calibration period, a switch disconnects the antennas and substitutes a broadband noise source. This provides a known signal level across all measurement frequencies. Since the noise diode calibration signal passes through exactly the same signal path as the received signal, this technique accurately compensates for all features of the signal path--regardless of the amount of attenuation or gain present in a given channel. The only uncalibrated parts of the signal path are the antennas themselves and the short lead-ins between antennas and calibration box inputs.

Most of the remainder of the receiver is contained in a series of modules that fit into a commercial instrument chassis. The signals first pass through a signal-conditioning module where the desired signals are separated from other frequencies with rf bandpass filters (typically 20 MHz wide) and

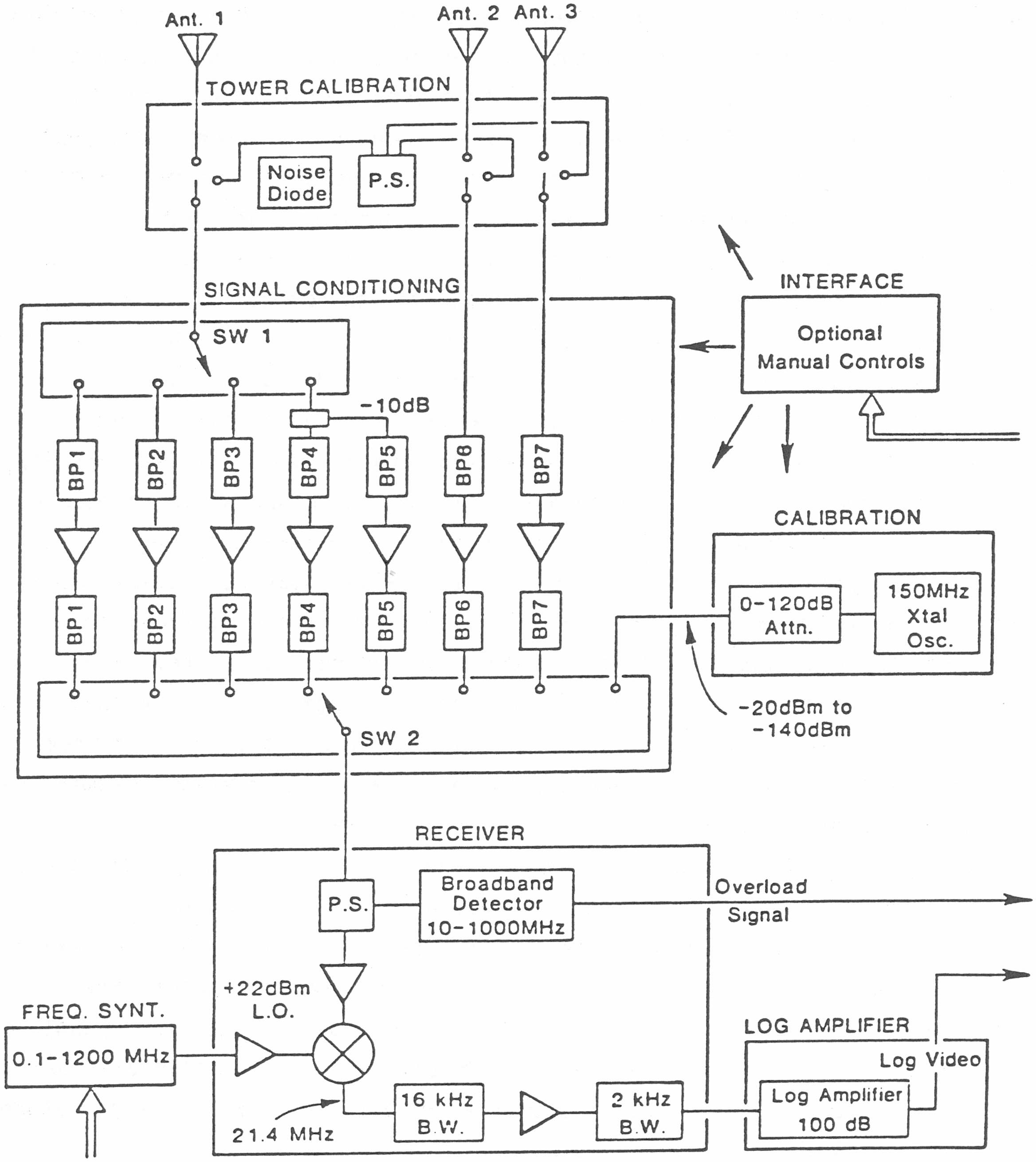

Figure 6. Block diagram for the receiver subsystem of the Automated Propagation Measurement System.

amplified with low-noise preamplifiers. The exact bandpass filters used will vary with the frequencies selected to be received at each site, and therefore the module is constructed so as to allow easy replacement. In Figure 6 the switch SW1 is a very long-life mechanical rf switch that has a high insertion loss and should resist possible intermodulation products from strong out-of-band signals. The rf switch SW2 is a simple PIN-diode switch that can be used here because insertion loss and intermodulation performance have already been assured by the preceding signal conditioning.

The receiver module is a single-conversion, superheterodyne receiver with a 21.4 MHz IF frequency. A final bandpass of 2 kHz provides a measurement noise floor at about -118 dBm. Meaningful output from the system presupposes well-known and stable source transmitter frequencies. Part of the rf signal is split off for a broadband detector. This detector senses the total power in the rf band-pass and indicates a possible overload problem if too much signal power is present. The receiver frequency is precisely selected by the local oscillator frequency, which is provided by a commercial frequency synthesizer. The output of the synthesizer is amplified to +22 dBm for high-level mixing to reduce the susceptibility to intermodulation products.

The IF signal is converted to a DC voltage by the logarithmic amplifier module with a 100 dB dynamic range. Operation over this very large dynamic range assures accurate measurements even if input signal amplitude changes over a very wide range. The logarithmic amplifier module also contains an audio amplifier and a loudspeaker, which may be useful for diagnostic purposes.

The calibration module contains a 150 MHz signal source and a 120 dB step attenuator. These provide a known calibration signal over a -20 to -140 dBm range and will characterize the log amplifier response in 10 dB steps.

The entire receiver can be controlled manually or automatically via a computer program. When the receiver is being used for measurements, it will normally be under computer control. Testing and trouble-shooting are often easier under manual operation. Many of the manual controls are located on the digital interface module. Other controls are positioned on the modules that they control.

The module chassis contains power supplies and interconnection wiring used by the modules. Most of the IF and rf signal paths go through coaxial cabling on the front panels of the modules, because the connectors on the back of the modules are not designed to handle radio frequencies.

A high-accuracy frequency synthesizer is the last major subassembly of the measurement system. This instrument generates the required local oscillator (LO) frequencies, as commanded by the computer via an IEEE-488 data bus. The synthesizer is a standard instrument, although an internal jumper has been positioned to speed up tuning and accuracy at the expense of some (unused) modulation capability.

A microprocessor-based control and analysis system operates the receiver. Under the control of measurement programs stored in ROM (Read Only Memory) and magnetic bubble memory, the receiver is cycled through a preestablished sequence of measurement frequencies, using proper antennas and signal-conditioning paths. At the beginning of each hour a complete system recalibration is accomplished with a combination of calibration techniques involving the noise diodes and the 150 MHz calibration oscillator. These frequent calibrations should keep the signal level measurements accurate in the face of possible system gain drift.

Laboratory testing of the receiver system with known signal inputs indicates that the recorded signal level can be up to 4 dB away from the signal level injected at the antenna calibration box. The magnitude of error is more pronounced when low-level signals are being monitored. For example, the widest discrepancy between actual signal level and recorded signal level occurred in a test at 687.24 MHz. A -90 dBm signal was injected at the antenna calibration unit, and statistics of its measured level were recorded in the automatic measurement mode over a standard 50-min test cycle. While the record showed a signal level greater than -90 dBm for more than 99% of the time, it also indicated a level greater than -86 dBm for 5% of the time. Hence, one should keep in mind that some degree of error, perhaps up to as much as 4 dB, may be associated with much of the automated propagation measurement system data.

3.2 Paths

There were somewhat more than 30 paths whose signals were used for this program. Of these we would like to describe here 14 that are interesting for our purposes and for which we seem to have a useful number of valid data.

The three San Diego receiver sites were located in three rather different local environments. The first was at the FCC Field Office located in a fivestory building in La Mesa, a suburb on the northern edge of San Diego. The second was part of a small antenna farm on Cowles Mountain, a small mountain (477 m high) northeast of La Mesa. And the last receiver site was on Point Loma, a United States naval reservation on the Pacific Ocean at the northwestern corner of San Diego.

The transmitters were all "signals of opportunity" derived from television stations. Now, the use of television transmitters as signals for propagation studies has its advantages and its disadvantages. Among the advantages are high radiated power, very good frequency stability, and a sharply localized spectrum. A UHF television station will often have an effective radiated power (ERP) of as much as 5 MW and almost all of this power will be localized in the video carrier. There are, however, at least two disadvantages. First, a station is not normally in operation for the full 24 hours of the day and there will be regular gaps in the record. Indeed, operating hours for some of the stations observed in the present program were rather short. The second concern is with the antenna patterns. These may be omnidirectional in that they radiate equally in all azimuthal directions, but they are almost always high gain antennas with a sharp beam in the vertical plane. Beam widths can be 2° or even less. If an antenna is on a mountain overlooking the area to be served, it will often employ electrical beam tilting and direct the beam downward by 1° or 2° toward the desired service area. Since we are interested here in interference fields where elevation angles to shielding terrain obstacles may be out of the ordinary and where a layered atmosphere may bend the rays in unusual directions, it is therefore difficult to say how one should treat these narrow beams. In particular, it seems questionable whether one can immediately transfer results obtained by a study of such television transmitters to the case of the mobile services where lower gain antennas are normally used.

The paths extend along the California coast between Los Angeles and San Diego, and they are subjected to a radio climate dominated by what is called the "marine layer." This is a layer of marine air trapped by a temperature inversion that extends along the coast and out into the Pacific Ocean. Its depth undergoes considerable variabiliy with an average near Los Angeles of about 500 m. Accompanying it there often appear one or more super-refractive layers that may then affect radio waves. Winter storms, of course, will blow away the marine layer leaving only a "normal" atmosphere.

3.2.1 KEYT(3), Santa Barbara

Although the principal purpose of the program was to measure UHF signals, we did observe a few VHF stations. One of them, KEYT(3), operates at the particularly low frequency of 61 MHz. It was made part of the program because of a particular need of the FCC to study the effects a proposed San Diego based Channel 3 station would have on the environment.

The station is network affiliated, radiates maximum permitted power, and normally operates from 0600 to 0100 local time. It serves Santa Barbara and the adjacent coastal cities some 140 km northwest of Los Angeles. The antenna is on TV Peak in the Santa Ynez Mountains at an altitude of 1324 m. It should be above the marine layer most of the time.

The station was received at both Cowles Mountain and Point Loma. In Figures 7 and 8 we show the terrain profiles of the two paths. Note that they can both be characterized as long (330 km) oversea paths with horizons on the water.

3.2.2 KABC(7), KWHY(22), and KLCS(58); Mt. Wilson

These three television transmitters are all located in the antenna farm on Mt. Wilson northeast of Los Angeles. Their widely separated carrier frequencies should provide us the opportunity to describe directly how received signal levels vary with frequency.

KABC (175 MHz) is network affiliated, transmitting maximum permitted power. It is another of the VHF stations observed. Its normal operating hours are from 0530 to 0330, and this station is the most nearly continually operating of all the broadcast stations observed. It was received at all three San Diego sites.

KWHY (519 MHz) is an independent station that operates as a subscription television station using a scrambled signal in the evenings. It transmits maximum permitted power and normally operates between the hours 0630 and 2430. It was received at both La Mesa and Cowles Mountain.

KLCS (735 MHz) is a public television station operated by the Los Angeles Unified School District. It transmits at nearly the maximum permitted power; unfortunately, its operating hours are rather short, from 0730 to 2130 and even less on the weekends. It was received at all three receiver sites.

The three antenna towers are all very close together almost 1800 m above sea level. The eight paths involved (examples of which are shown in Figures 9, 10, and 11) are all very similar. They are about 185 km long, but because